

CONFIRMATION OF THE 62 DAY X-RAY PERIODICITY FROM M82

PHILIP KAARET AND HUA FENG

Department of Physics and Astronomy, University of Iowa, Van Allen Hall, Iowa City, IA 52242.

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ABSTRACT

Using 400 days of new X-ray monitoring of M82, we confirm the 62 day periodicity previously reported. In the full data set spanning 1124 days, we find a period of 62.0 ± 0.3 days and a coherence, $Q = 22.3$, that is consistent with a strictly periodic signal. We estimate that the probability of chance occurrence of our observed signal is 6×10^{-7} . The light curve folded at this period is roughly sinusoidal and has a peak to peak amplitude of $(0.99 \pm 0.10) \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$. Confirmation of the periodicity strengthens our previous suggestion that the 62 day modulation is due to orbital motion within an X-ray binary.

Subject headings: black hole physics – galaxies: individual: M82 galaxies: stellar content – X-rays: galaxies – X-rays: binaries

1. INTRODUCTION

Bright, non-nuclear X-ray sources in external galaxies, the so-called ultraluminous X-ray sources (ULXs), represent either intermediate-mass black holes (Colbert & Mushotzky 1999; Makishima et al. 2000; Kaaret et al. 2001) or super-Eddington accretion onto stellar-mass black holes. The brightest X-ray source in the nearby starburst galaxy M82, CXOU J095550.2+694047 = X41.4+60 (Kaaret et al. 2001), is one of the most extreme ULXs. Assuming isotropic radiation, a black hole mass of at least $500 M_{\odot}$ is required to avoid violating the Eddington limit. The source also shows quasiperiodic oscillations (QPOs) at relatively low frequencies, 50-190 mHz, suggesting a relatively high compact object mass (Strohmayer & Mushotzky 2003; Dewangan, Titarchuk, & Griffiths 2006; Mucciarelli et al. 2006; Kaaret, Simet, & Lang 2006b). The relative proximity and brightness of source enables studies that are not feasible for other ULXs.

We monitored the X-ray emission from M82 for 240 days in 2004/2005 and detected a period of 62 days (Kaaret, Simet, & Lang 2006a). We interpreted the 62 day period as the orbital period of the ULX binary system. For a system in Roche-lobe contact, such a long orbital period implies a low density companion on the giant or supergiant branch. Identification of the evolutionary phase of the companion star represents a significance advance in our knowledge of ULXs. In order to test this interpretation of the 62 day periodicity, we obtained additional monitoring of M82 in 2006/2007. We describe the new X-ray observations in § 2 and discuss the results in § 3.

2. OBSERVATIONS

We obtained 187 observations of M82 using the Proportional Counter Array (PCA) on the Rossi X-Ray Timing Explorer (RXTE) covering MJD 53825 to 54223 with observations approximately every other day under RXTE program 92098. The observations were typically less than 1 ks. We also analyzed archival data from RXTE program 90121 which consists of 144 observations roughly every other day from MJD 53252 to 53490 and two observations made earlier. In this earlier program, the ob-

servations were typically about 2 ks each.

We used the RXTE production data and processed the data using HEASoft version 6.2. We selected good time intervals where the time since the last SAA passage was more than 30 minutes, the electron contamination was less than 0.1, and the pointing was within 0.1° of the target and at least 10° above the horizon. We produced spectra using only the top layer in Proportional Counter Unit 2 and estimated the background using the faint source background model. We fitted the spectra using XSPEC 11 in the energy range 2.6–20 keV with a power-law model with an interstellar absorption column density fixed to $3 \times 10^{22} \text{ cm}^{-2}$. The best fit model was used to calculate the absorbed flux in the 2-10 keV band.

Fig. 1 shows the flux in the 2-10 keV band versus time. We note that, due to the large angular acceptance of the PCA, the measured flux includes contributions from all X-ray sources within M82. Thus, some part of the fluctuations represents sources other than X41.4+60. There is an X-ray flare around MJD 53400 which was discussed in Kaaret, Simet, & Lang (2006b). Points with fluxes above $4 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$ were removed in the subsequent analysis. The photon index is generally between 2.0 and 2.7 with an average value of 2.4. The distribution of the measured photon indexes are consistent, within the uncertainties, with a constant value of 2.4.

The light curve shows an apparent modulation with a period near 60 days. Fig. 2 shows a periodogram with the power normalized by the total variance of the data (Horne & Baliunas 1986). There is a peak at a period 62.0 days with a power of 77.9. We estimate the 90% confidence error on the period to be 0.3 days. There are two secondary peaks near the main peak which are aliases due to the gap in the monitoring. Retaining the X-ray flare near MJD 53400 does not shift the peak, but decreases the power (because of the normalization to the total variance of the data) to 70.5. Using fluxes calculated from spectral fits with the photon index fixed to 2.4 does not significantly change the period or the power of the peak.

We tested the significance of the observed signal using a red noise background, as is appropriate for an accreting X-ray source (Israel & Stella 1996; Vaughan 2005).

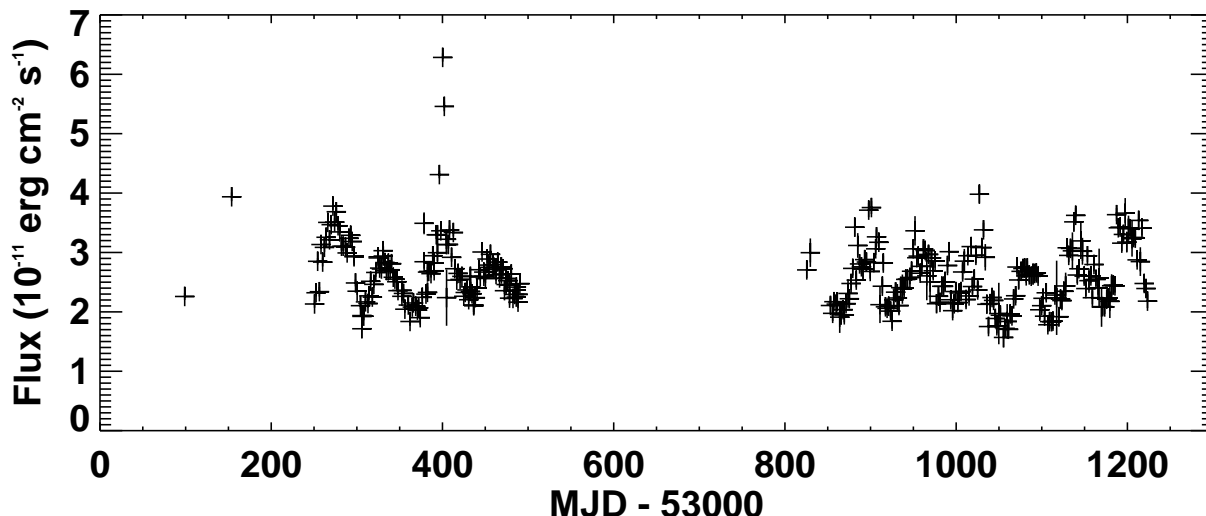


FIG. 1.— Light curve of M82 in the 2–10 keV band. The plot shows the flux measured using the PCA for each observation versus the observation date in MJD. The flux includes contributions from all X-ray sources within M82.

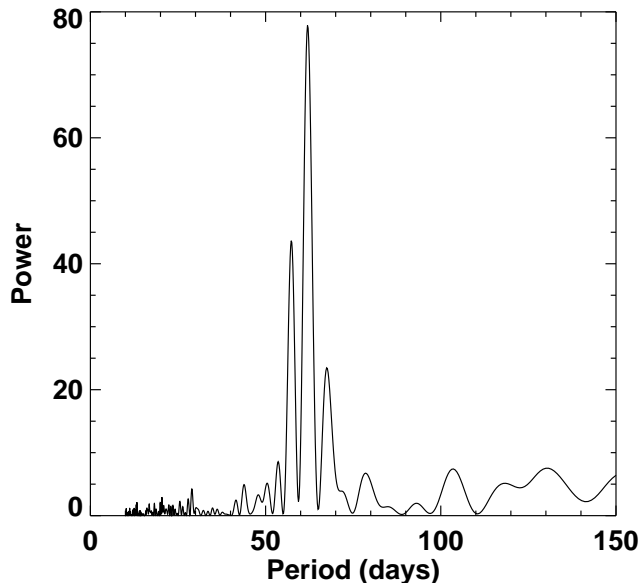


FIG. 2.— Periodogram of the 2–10 keV light curve of M82. The strongest peak is at a period of 62.0 ± 0.3 days. The two secondary peaks near the main peak are aliases due to the gap in the monitoring. The powers are calculated using the method of Horne & Baliunas (1986) and are normalized by the total variance of the fluxes.

We fitted the power versus frequency relation for periods in the range 6–280 days to a power-law form and found a spectral index of -1.04 ± 0.06 . We generated red noise with a spectral index of -1.10 and with mean and variance equal to those of the data using the `rndpwr1c` routine of the `aitlib` IDL subroutine library provided by the Institut für Astronomie und Astrophysik of the Universität Tübingen (Timmer & König 1994). The duration of each generated light curve is longer than the actual data in order to minimize the effects of red noise leakage. Each light curve contains 8192 data points with uniform spacing of 0.66 days and a subset of 330 points from the middle of this set with relative times matching the actual observations are extracted for analysis. These 330 simulated fluxes were processed with the same procedures used to analyze the real data. We generated 2×10^6 trial light curves and searched for cases where the power at periods of 10 to 150 days was greater than

or equal to the observed value of 77.9. We found one such case and estimate the probability of chance occurrence of our observed signal to be 5×10^{-7} . Fitting the distribution of maximum observed powers, we estimate that the probability of chance occurrence of our observed signal is 6×10^{-7} , in good agreement. This procedure is conservative because it includes the signal in the calculation of the power-law slope and the variance and because the period search range, 10–150 days, extends to significantly lower frequencies than the observed period where the red noise produces high amplitude fluctuations. If we restrict the search range to periods of 62 days or less, then a fit to the distribution of the maximum observed powers indicates that the probability of chance occurrence of our observed signal is 3×10^{-13} .

The coherence or quality value of the peak signal, the period of the peak divided by the full width at half maximum power, is $Q = 22.3$. This is fully consistent with that expected for a periodic process given the observation duration.

Fig. 3 shows the data folded at the best fit period. Each point is the average flux of the observations falling within the given phase bin and the error bar is the standard error, i.e. the standard deviation of the fluxes in each bin divided by the square root of the number of fluxes in that bin. The amplitude of the modulation, taken as the maximum average flux in one bin minus the minimum, is $(0.99 \pm 0.10) \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$.

To search for rapid variability, we extracted event files with high time resolution data for the 187 observations. Events in the 2.4–11.9 keV energy band were selected in the good time intervals defined above and split into segments of 256 s. An FFT with a time resolution of 1 s was calculated for each segment. The FFTs within each observation were added incoherently. The resulting total power spectrum was logarithmically rebinned with a bin width of 16%, equal to the widths of the QPOs previously detected from M82. We searched for individual bins with high powers and calculated the significance taking into account the number of bins in each power spectrum. The highest power was recorded on MJD 54155.148 in a single 256 s interval of data at a frequency of 20 ± 4 mHz with a Leahy power of 19.7 corresponding to a chance

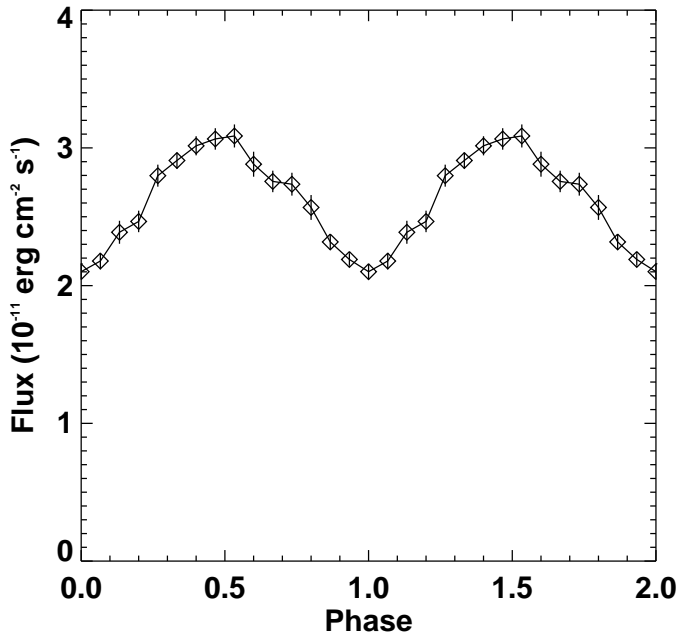


FIG. 3.— Flux from M82 folded at a period of 61.98 days. Two periods are shown for clarity. Each point is the average flux of the observations falling within the given phase bin and the error bar is the standard error.

probability of occurrence of 5.4×10^{-5} (4.0σ) single trial and 0.0012 taking into account the trials for that single observation. Taking into account all observations in program 92098, the chance probability of occurrence is 0.23 indicating that the QPO detection is not significant. The observations in the new RXTE program are too short to provide good sensitivity for QPO detection.

3. DISCUSSION

Using 400 days of new X-ray monitoring of M82, we confirm the 62 day previously reported (Kaaret, Simet, & Lang 2006a). The coherence of the signal, $Q = 22.3$, is consistent with a strictly periodic signal. The light curve folded at this period is roughly sinusoidal and has a peak to peak amplitude of $1.0 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$. The new observations rule out the possibility that the signal could be red-noise fluctuation. The remaining possible interpretations of the signals are that it represents either the orbital period of the binary system or a superorbital modulation.

Superorbital modulations are most often interpreted as due to accretion disk precession (Wijers & Pringle 1999; Ogilvie & Dubus 2001) and, in this case, would represent variations in our viewing angle of the disk. Indeed, in the one source where both a precessing relativistic jet (thought to be launched perpendicular to the disk) and a superorbital modulation are detected, SS 433, the periods of jet precession and superorbital modulation are the same (Margon & Anderson 1989). If ULXs are beamed sources, then the beaming cone would most naturally be perpendicular to the disk axis. Thus, accretion disk precession would naturally produce modulation of the beam at the superorbital period.

The distribution of superorbital periods of neutron star and black hole candidate X-ray binaries are plotted in Fig. 4 (Wijers & Pringle 1999; Smith, Heindl, & Swank 2002; Corbet 2003; Rau, Greiner, McCollough 2003). We include only black hole candidates as defined by

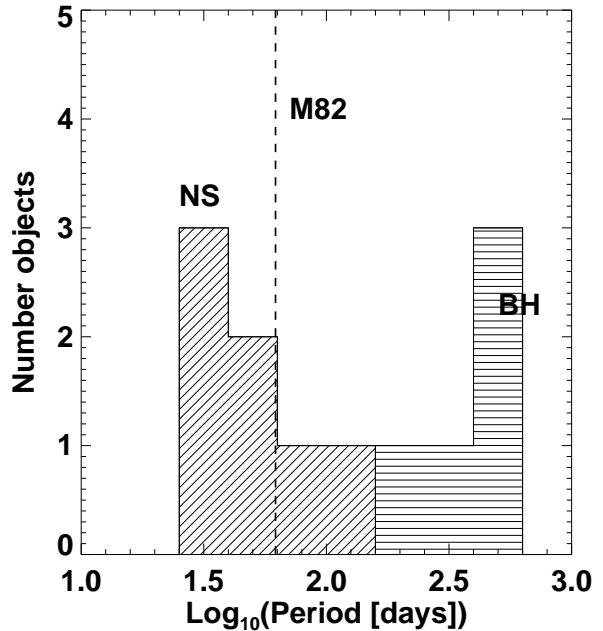


FIG. 4.— Distribution of superorbital periods of neutron star binaries (diagonally hatched) and black hole candidate binaries (horizontally hatched). The vertical dashed line shows the period measured from M82; it falls in the neutron star binary range.

Remillard & McClintock (2006). It is apparent from the figure that there are no black hole binaries with superorbital periods near 62 days. The shortest superorbital period from a dynamically confirmed black hole candidate is the 198 day period of LMC X-3 which is longer by more than a factor of 3. Thus, if the 62 period from M82 is interpreted as a superorbital period, this would suggest that it arises from a neutron star system. The measured flux modulation implies a luminosity (assuming isotropic emission) of $1.6 \times 10^{40} \text{ erg s}^{-1}$ for a source in M82 at a distance of 3.63 Mpc. This would exceed the Eddington limit for a $1.4M_{\odot}$ neutron star by at least a factor of 86. The brightest known neutron star transient is A0538-66 which reached a peak luminosity of $8 \times 10^{38} \text{ erg s}^{-1}$ (White & Carpenter 1978), a factor of 20 lower than X41.4+60. Compared instead to the peak luminosity of flares from X41.4+60, the peak luminosity of A0538-66 is a factor of 95 lower. Thus, a neutron star interpretation for X41.4+60, as would be expected if the 62 day period is a superorbital modulation, is untenable.

When monitored over many periods, superorbital modulations show reduced coherence in the form of period or phase shifts. The high coherence measured for the M82 periodicity is inconsistent with all but the most stable of the superorbital modulations, specifically that of Her X-1.

Several X-ray binaries produce X-rays modulated at the orbital period including Cygnus X-3 (Elsner et al. 1980), LMC X-3 (Boyd, Smale, Dolan 2001), 1E 1740.7-2942 and GRS 1758-258 (Smith, Heindl, & Swank 2002), and GX 13+1 (Corbet 2003). Thus, the periodicity from M82 may be interpreted as due to orbital modulation. The coherence of the signal we observe from M82 is consistent with that expected for a strictly periodic signal given the observational coverage. This is consistent with interpretation as an orbital modulation. We conclude that the 62 day periodicity most likely indicates the orbital period of an X-ray binary. If the com-

panion fills it Roche-lobe, as expected in a system with a mass accretion rate high enough to produce the observed X-ray flux even with moderate beaming, then the long period indicates that the companion star has a low average density, $5 \times 10^{-5} \text{ g cm}^{-3}$, and is therefore a giant or supergiant.

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